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Spatial Orientation and Off-Axis Challenges for NOTES

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Spatial orientation was identified as a special concern or developmental barrier to the introduction of natural orifice transluminal endoscopic surgery (NOTES) in the consensus document generated by the 2005 Natural Orifice Surgery Consortium for Assessment and Research (NOSCAR) group, a joint committee created by the American Society for Gastrointestinal Endoscopy and the Society of American Gastrointestinal and Endoscopic Surgeons [1]. These issues were identified through conceptual concerns generated by early concepts where NOTES was performed with the endoscope in a retroflexed position, resulting in a horizon that was infinitely variable and by the loss of virtual three-dimensional (3D) perception with parallel optics and instrumentation.

Knowledge of human factors derived from laparoscopic studies has long established that efficiency and accuracy of surgical maneuvers decrease as the visual field is rotated and the task is more complex [2]. This effect is especially prominent when two or more instruments are used in conjunction with frequent scope readjustment. Horizon orientation has not traditionally been an issue with flexible endoscopy. Although this is in part a result of habituation on the part of endoscopists, it is also a factor of the tubular nature of the gastrointestinal tract and the single instrument nature of most endoscopic procedures. These factors make the orientation of the instrument channel more critical to the endoscopist than the angle of approach to the surgical target. It is only rotation of the scope that gives one any hint at a 3D degree of freedom (beyond simple in and out) because of the very slight off-axis nature of the biopsy channel (Fig. 1).

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This movement far exceeds the importance of a fixed horizon when it comes to operating on what can somewhat simplistically be described as typically two-dimensional (2D) objects in a fairly featureless “tube.” Consider this example: for a snare polypectomy, the endoscopist targets the polyp; advances the optic directly toward it; deploys the snare; and then, while maintaining the center of the poly as visual center, uses advancement, withdrawal, and “torque” to fine-tune placement of the snare around the polyp. This is all done while ignoring the structural context around the polyp. Contrary to this, most laparoscopic procedures occur in a highly complex visual environment and aside from simple biopsy usually require complex 3D dissection using two hands.

Such dissection often depends on a knowledge-based “mapping” of not only the visualized structure but also adjacent structures and hidden structures beneath the surface. In this regard a fixed horizon is more important than a central target zone because it acts as a stereotactic reference point that allows the surgeon constantly to superimpose their “knowledge map.” An example of this is dissection of the triangle of Calot during a laparoscopic cholecystectomy. In this case the view is carefully fixed with the dissection area in the center but the horizon carefully maintained as normal. The surgeon is intimately aware of the position of the cystic duct, cystic artery, common duct, and so forth even though it is initially obscured by overlying tissue by unconsciously comparing what he or she is looking at with a mental map built from merged memory of other cases (Fig. 2). For this unconscious superimposition to have maximum accuracy the field of view needs to stay fixed, particularly the horizon. It is certainly true that the surgeon can perform the surgery if things such as the horizon are not perfect, but this requires the surgeon to mentally calculate the conversion of what he or she is seeing to what their memory map supplies. This dramatically increases mental workload, which slows the dissection down and makes the procedure more prone to error [3].
This processing difference is a central reason for the important difference between the endoscopic paradigm and the laparoscopic paradigm. Endoscopy is typically performed with the endoscopist controlling both the visualization and the instrument manipulation, with the assistant passively performing simple tasks on command. This is necessitated because manipulation of the scope is the most complex and knowledge-dependent task and the instruments are directly tied to movement of the surgeon’s “eye” [4]. Laparoscopy, however, uses an assistant who is a camera driver, responsible for
maintaining the field of view and the orientation. The surgeon performs the task of running the instruments, which is the more complex task because of increased range of instrument motion, paradoxical movement necessitated by the instruments pivoting at the body wall and from the actions being divorced from the optics. NOTES, although a flexible endoscopic procedure, may require a move away from the endoscopic paradigm to a more laparoscopic one to decrease the mental workload of the surgeon and share it more equally with the assistant (the camera person). An interesting difference from the laparoscopic paradigm is that the skill-set required from the NOTES camera operator is much greater than the skills needed for a laparoscopic camera person, traditionally thought of as a job for the intern or nurse. With NOTES the camera driver may have to be as skilled as (or even more skilled than) the surgeon. This has led many to postulate that NOTES may require a team effort with a scope expert and a surgery expert. This need will be modified by technologic developments, which may decrease the work needed by the team, particularly the endoscopic skills component [5].

Off-axis visualization is a different issue but lack of it leads to the same end results: increased mental work load for the physician and degrading of efficiency and accuracy of the procedure [6]. Laparoscopic surgeons often encounter this phenomenon with mispositioning of trocars, placing them either too close to the camera (parallelism) or to one side or the other (off center), either of which can lead to disorientation and difficulty with precise task completion. It has long been taught that the ideal configuration for advanced laparoscopic surgery has the camera located centrally, with the axis parallel to the surgeon’s line of sight and with the two instruments inserted on either side at an angle of 45 degrees (Fig. 3) [7]. Ideally, the view should also look down on the instrument tips. There are several reasons why this is the optimal configuration for laparoscopic surgery including the fact that it feels more natural (hands and arms being equidistant from the eyes and below the visual plane) and it is more comfortable, which leads to less fatigue and skill degradation. Perhaps a more important reason is the role off-axis visualization plays in depth perception. The ability to make precise movements endoscopically is a learned ability that involves the operator accurately translating a 2D video view into a 3D mental construct that reflects the patient’s apparent and expected anatomy. The ability of the brain to translate 2D into 3D depends on the ability of the eye to pick up additional visual clues that are translated by the occipital lobe into essentially the same image received by binocular vision [8]. This is why image resolution is critical in video endoscopy: the higher the resolution, the more (and more subtle) visual clues the brain has to work with to translate the image into a 3D construct. Axial vision greatly reduces the environmental relationships available to serve as data to enable easy mental translation to 3D perception. Complete parallelism, where an instrument exits through the center of the imaging lens, makes precise instrument use very difficult because depth perception input is restricted to
parallax (the perception that faraway objects are smaller than nearer ones). Even the small offset of the instrument channel and the lens in modern endoscopes greatly improves the ability accurately to use an instrument. At its optimal offset of 45 degrees, there are the maximal inputs to use for one’s mind to calculate accurately position of instruments, which can be translated as “good (easy) depth perception” (Table 1). This is analogous to how a person who has single eye vision both perceives and functions.

A fixed instrument port location equidistant from the optic, 45 degrees off-axis, with a high-resolution optic and a “camera person” focused on maintaining a stable horizon would dramatically reduce the mental workload of NOTES and improve efficiency and decrease errors. Unfortunately, there currently exists no such device and there are many developmental hurdles to cross before such a device is available.

Table 1
Visual clues in a 2D environment available for mental translation into a three-dimensional construct

<table>
<thead>
<tr>
<th>Clue</th>
<th>Offset instrument</th>
<th>Parallel instrument</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parallax</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Light reflections on tool</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Cast shadows</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Direct view of instrument tip</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Tip relations to known anatomic structures (context placement)</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>
Current design options for optimal natural orifice translumenal endoscopic surgery visualization

Because there is no immediate hope of having the perfect device, what then are the engineering or practical options for the near future? Because off-axis visualization and horizon control are different issues addressed somewhat separately by engineers, possible options are addressed independently.

Image horizon

The optimal imaging state is maintenance of a constant, normal horizon. There are several ways of accomplishing this but by far the simplest is to alter the placement of the endoscope with the intent of optimizing the functional view. An illustration of this is the concept of transgastric cholecystectomy where the scope exits the most dependent portion of the stomach and then retroflexes from the lower abdomen to visualize the gallbladder. This results in an inverted image on the screen but normal instrument position. Alternatively, the scope can be placed transrectally or transvaginally, which results in normal orientation [9]. For transgastric approaches, the authors have found that exiting the mid to proximal stomach allows the gallbladder to be visualized with a 45- to 90-degree lateral flexion, once again maintaining nearly a normal horizon. Finally, although an altered horizon does increase the mental workload, this can be compensated for by repetitive practice that maximizes the brain’s efficiency at translating the image to a normal horizon much as it does when it translates a 2D video image to a 3D mental construct. With enough practice, an endoscopist can be retrained to perform a cholecystectomy accurately in a retroflexed fashion with good efficiency. It does, however, take many years of practice to make this truly automatic, and because of the hidden mental work going on, performance is never equal that of dissection done in a normal position.

There are engineering efforts being explored to allow endoscopists to establish a normal horizon no matter the angle of approach. These include adjusting the image on the video screen by turning the screen (which can be done mechanically or electronically). This is a technique used frequently with fluoroscopy to adjust the image to a normal referent no matter the position of the c-arm. The downside to this is that the action of the scope controls and instrument channels becomes divorced from the image and requires “relearning” or “recalculation” to perform tasks; anatomy recognition comes at the price of increased difficulty with manipulation. Another strategy is to rotate the endoscope itself relative to the instrument channels. This is the approach taken with the Transport endoscope (USGI Medical, San Clemente, California), which uses a 6-mm daughter endoscope that can be torqued by the camera person to keep the image upright (Fig. 4) [10]. The scope controls remain normal but the instrument ports do change
position relative to the image. Because the instruments only have two degrees of motion (in and out) this is a relatively easy distortion for which to compensate.

The ultimate solution for these issues is the use of a computer interface between the endoscopist and the end-organ to assume a large portion of the translational calculations needed to compensate for horizon distortion [11,12]. Such a robotic endoscope has the theoretic ability to present the endoscopic surgeon with a totally normal view of the operative field and natural intuitive operation of all controls in spite of the actual orientation and position of the scope and instruments. This advantage comes at the price of large size, years of development, and massive costs.

A somewhat related issue is the need to work out the optimal interaction between surgeon and assistant for NOTES procedures. The most common NOTES scenario involves the use of a dual-channel endoscope with a grasper and energy source through biopsy channels. With a standard endoscope these instruments are manipulated with the scope controls, by advancing and retracting each and by torquing the scope, which gives some artificial independent motion but at the cost of disrupting the visual horizon. These actions can be even more complex with the use of some of the three-dimensional endoscopes, which have additional controls allowing independent motion of the instruments (Fig. 5). The complexity of all this, especially when dealing with difficult anatomic dissection, quickly overwhelms the mental and motor abilities of most surgeons.

An alternative is to divide the tasks between the visualization and the instrument manipulation. In this scenario, once the endoscope has the operative field fixed in position, the endoscopist concentrates on maintaining the field of vision while the operator manipulates the instruments. Close team work and communication are needed [13]. Such a team effort is particularly needed in extreme distortion situations, such as operating in the retroflexed
position, where even the use of the scope controls becomes counterintuitive and requires extreme concentration. Once again, the ability to correct the view of the horizon, to know the action of the controls, and to be able to predict the position of the instrument tips dramatically facilitates the ability to perform complex surgeries.

**Off-axis visualization**

Even the most sophisticated computer processing is not able to supply the depth perception that is obtained with off-axis visualization. This requires an engineering solution. It is easy to note that even a small amount of axis deviation can dramatically increase accuracy, but more research is needed to determine the optimal amount of such offset. Options being explored include the use of a second flexible endoscope. This has the advantage of being readily available and of providing a second set of instrumentation at a different angle. The disadvantage is the requirement for a second endoscopist and assistant.

Alternatively, the idea of using insertable remote cameras that could be clipped to the peritoneum in different positions has been raised. This would potentially allow the surgeon to switch between different views and potentially triangulate to improve accuracy. A definite advantage with this possibility is the ability also to see the scope’s position in the abdomen, which is impossible to see when the image is from the scope’s tip. There are, however, several problems with this concept: the time it takes to set up extra cameras,
the need to adjust or control the camera and endoscope, and the lag time both to switch views and mentally to process such a remote image.

Another option is to have the ability to offset the image from the instruments built into the scope itself. This scope configuration replicates to some degree the setup of a laparoscopic surgery, with the scope positioned above and the instruments to either side (Fig. 6). There are several such prototype endoscopes in development, controlled either by mechanical “direct drives” or by more sophisticated computer-robotic interfaces [14]. In the short term these systems seem to offer the most benefit for the investment.

Summary

Issues of spatial orientation and off-axis visualization must be addressed to make NOTES more than a clinical oddity practiced by a highly skilled minority. The issue is the degree of mental work needed to operate with this new modality, with issues of depth perception and anatomy recognition currently making these procedures extremely difficult and unlikely to be practically applied or taught. New instrument designs and clinical tricks combined can dramatically decrease the mental work needed and make this closer to a widely learnable access method. In the long run, computer interfaces may be necessary to resolve some of these human factor issues and make a true universal platform.

References


